Technical Report No. 32-424

# Mariner Venus Power-Supply System

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## ABSTRACT

This Report covers the design, development, and integration of the components and subsystems comprising the power supply for *Mariner* Venus spacecraft. Data on the performance of the power system from launch until the end of mission are also presented in order to confirm the design.

# I. INTRODUCTION

The objective of the *Mariner* Venus project was to develop and launch two spacecraft to the near vicinity of the planet Venus in 1962, to receive communications from the spacecraft while in the vicinity of Venus, and to perform scientific measurements of the planet and interplanetary space. To support this project, a power system was designed to provide usable power to the spacecraft in the form of a 2400-cps square wave and 400-cps 3- and 1-phase sine waves. The power in flight was to be derived from solar cells arranged upon erectable panels. The attitude of the panels with respect to the Sun is dependent upon the attitude of the entire vehicle. A battery source was to be available to support the power requirements of the spacecraft from launch to Sun acquisition and midcourse maneuver when solar energy was not available because the spacecraft was oriented away from the Sun.

### A. Power System Configuration

In the *Mariner* Venus spacecraft power system, a cleaner interface between user and power source was attempted by distributing the power at a fixed ac voltage instead of the various dc voltage levels required by the users. The configuration for the *Mariner* power system has the form shown in Fig. 1.

The system provided the following voltages: (1) 28-v dc battery voltage which furnished power directly to the various short-term high-power loads, such as valves, relays, stepping motors, and squibs. (2) a 2400-cps square wave for operating transformer-rectifier circuits to produce the dc voltage desired by the user. (3) a 400-cps 3-phase sine wave which supplied power to the attitude control gyros. Single-phase antenna servos and scientific motors were supplied from one of the 3-phase outputs.

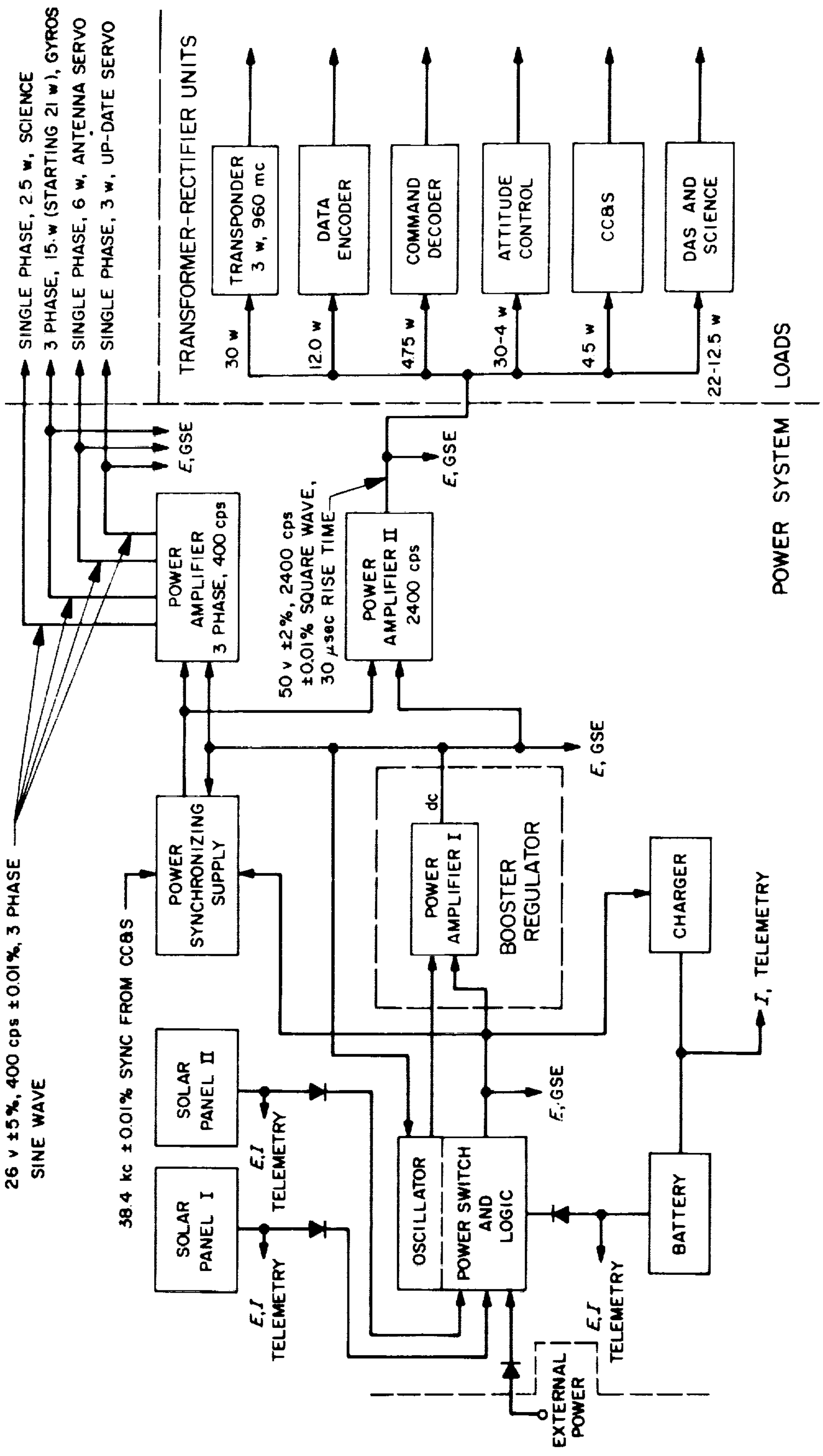


**Fig. 1. Power-supply block diagram**

With this arrangement the power supply development proceeded on a realistic schedule because of reduced interface problems with the users.

The power profile in Fig. 2 shows the raw power required from the 2400- and 400-cps systems, the battery load requirements, and the solar power available from the solar panels between Earth and Venus.

The input power during cruise mode was obtained from two solar panels with a minimum raw-power capability of approximately 200 w in Earth space and, at Venus, approximately 270 or 170 w, depending on the amount of degradation of solar cells.

From the solar characteristics, it appeared that the battery was expected to share the load with the solar panels during periods 5, 7, and 12. The battery was expected to be completely charged during period 4 and to have sufficient capacity to handle the periods of load sharing.

The weight allocated for the power system was 105 lb: 24 lb for electrical conversion equipment, 48 lb for solar panels, and 33 lb for battery sources.

### *B. Electrical Conversion*

The design and development of the electrical converters and associated subassemblies were performed at the Jet Propulsion Laboratory. The electrical conversion equipment was designed to operate in an environment of −10 to +55°C ambient; it was packaged into six modules of a combined volume of 727 in³. A reliability study on the design of the conversion equipment was

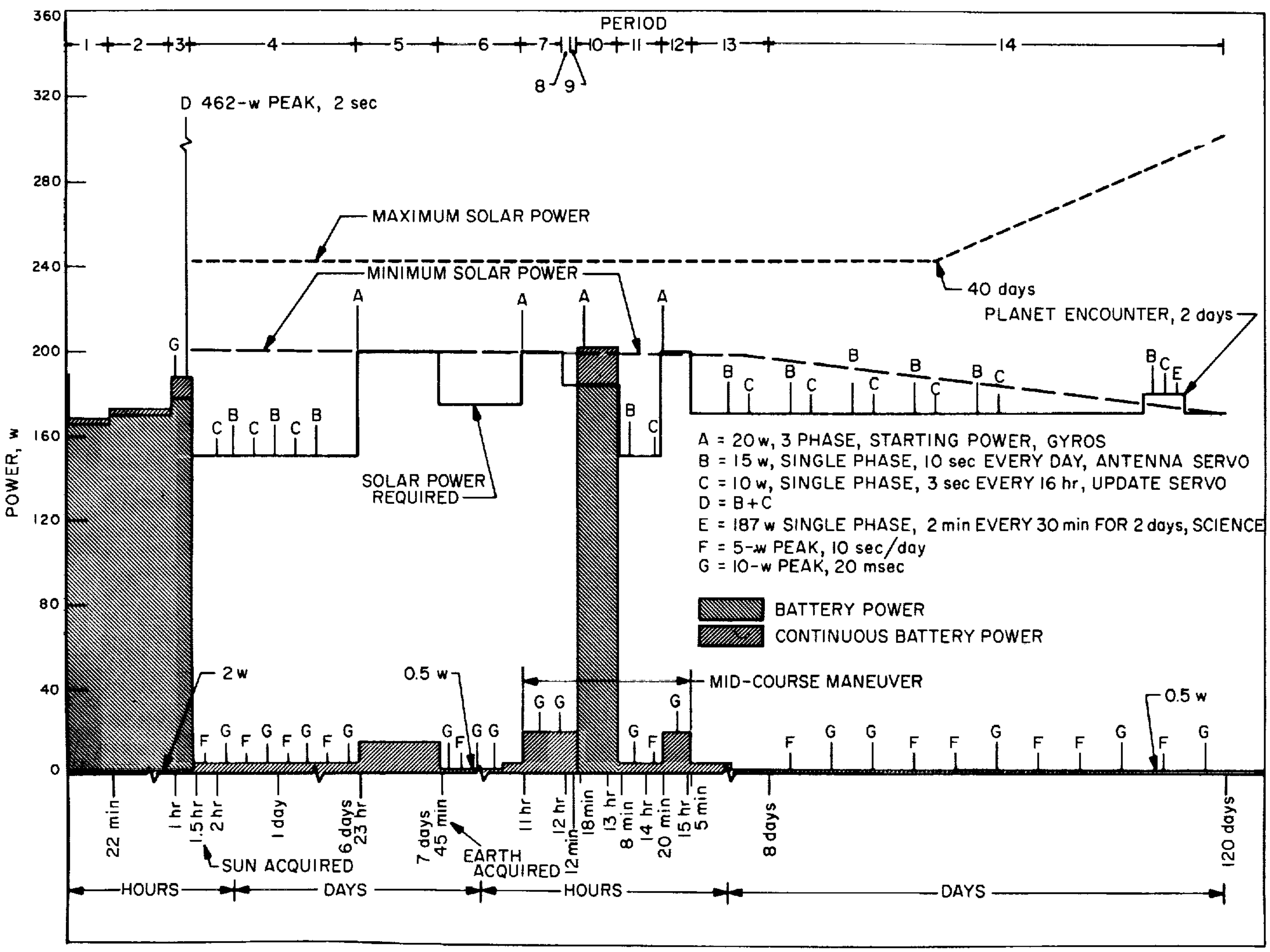


**Fig. 2. Load profile**

performed, and, from the derating factors used and the environment of operation, a mean life expectancy of 3180 hr was calculated, based on available data. A brief description of each subassembly follows.

**1. Power Switch and Logic (PS&L) Module**

This module received electrical power from the solar source, the battery, and the ground power unit, selected the power source, and provided the power to the booster regulator, the battery charger, and the synchronizer. Ground power was introduced into the power system through a motor-driven switch that was controlled from the ground. Another function of the module was to provide telemetry information for the following:

1. Solar panel voltage No. 1
2. Solar panel voltage No. 2
3. Solar panel current No. 1
4. Solar panel current No. 2
5. Battery current drain
6. Battery voltage
7. Battery charging current

**2. Booster-Regulator Module**

This module received the variable power voltage from the PS&L module, and provided regulated voltage ±1% to the 2400-cps power amplifier, 400-cps 3- and 1-phase power amplifier, and the synchronizer. The pulsed-width-modulation technique in the booster arrangement was used for efficiency.

**3. Synchronizer Module**

This module received a 38.4 kc ±0.01% square-wave signal from the control timer of the Central Computer and Sequencer (CC&S) subsystem and, with the use of countdown and magnetic oscillator circuits, provided square-wave base drive to the 2400-cps amplifier, and 3-phase square-wave base drive to the 400-cps 3- and 1-phase power amplifier. The frequency of the drive was controlled to ±0.01%. The synchronizer will free run at 2.2 kc in the absence of the control-timer signal.

**4. 2400-cps Power Amplifier**

This module received the frequency-controlled base drive from the synchronizer and regulated-power voltage from the booster regulator in order to provide 50-v ±2% rms square-wave voltage to the various transformer-rectifier users. The square wave output has an output impedance of 1 ohm and a maximum capacity of 125 w.

The users of the 2400-cps square-wave output are as follows:

| | |
|---|---|
| Communications | 30 w (max.) |
| Attitude control | 29 w (max.) |
| Central computer & sequencer | 7.0 w (max.) |
| Command decoder | 4.7 w (max.) |
| Data encoder | 10.0 w (max.) |
| Science | 22.5 w (max.) |

**5. 400-cps 3-phase–1-phase Power Amplifier**

This module received the frequency-controlled base drive from the synchronizer and regulated-power voltage from the booster regulator, in order to provide a 3-phase 26-v ±5% rms sine wave. By switching out two power amplifier stages the module converted to a single-phase power amplifier capable of providing 26-v ±15% rms sine wave.

The 3- and 1-phase sine-wave users are as follows:

| | |
|---|---|
| 3$\phi$ gyros | 13.5 w (max.) |
| 1$\phi$ antenna servos | 1.5 w (max.) |
| 1$\phi$ update servos | 1.5 w (max.) |
| 1$\phi$ scientific load | 4.1 w (max.) |

**6. Battery Charger**

This module provided a 1-amp maximum-current constant-voltage charge to the battery. This charge was reduced to a low rate and finally to a trickle charge of less than 5 ma as the battery voltage rose to the open circuit voltage.

## *C. Solar Panels*

The *Mariner* Venus spacecraft solar panels were designed with the benefit of only a small amount of experience with the *Ranger* panels, plus additional laboratory experimentation on the filter cement, the cell adhesive, the insulation material, and the method of cell mounting. The panels are approximately 60 in. long by 30 in. wide. The substrate was manufactured from aluminum for light weight, and Mylar was used for insulation before cells were positioned. The cells were applied to the panel with an adhesive.

The panel circuit called for a total of 4896 cells with 102 in series and 48 strings in parallel. The cells are 1- by 2-cm areas using P-layer contacts at the corners along the 1-cm edge with grids running the long way on the cell. The average electrical output of each cell was to be 22.9 mw at the maximum power point under tungsten light of 100 mw/cm$^2$ and 28°C cell temperature. To assure the power-output capability of the panel, selection of cells was necessary for uniform efficiency. The electrical connections of the series and parallel strings are shown in Fig. 3.

Each panel has two parallel connected areas. Each of these areas has three sections which are connected in series. This configuration was to be capable of producing 100 w per panel in Earth space, and 135 w per panel near Venus, with a maximum power voltage ranging from 49 v at Earth to no less than 35 v at Venus. Zener diodes were installed on the panels to reduce the output voltage of the solar source to 50 v. A power degradation during the flights to Venus was anticipated because of the higher stabilized temperature and by high-energy radiation.

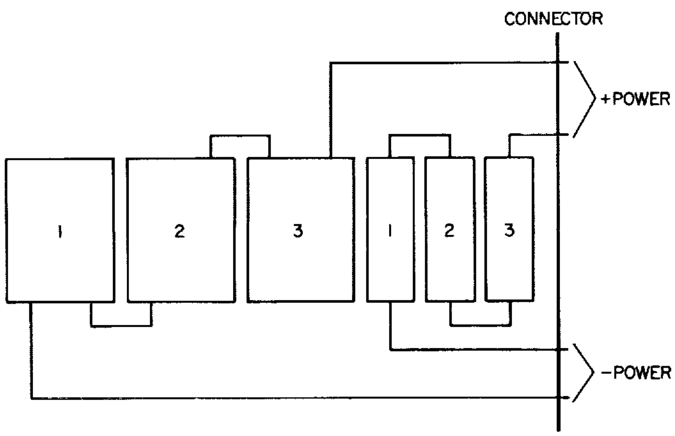


**Fig. 3. Solar-panel electrical connection**

Calculations of the above solar power capability were based on solar-panel temperature of 35°C in Earth space. However, Ranger 3 flight data indicated that the solar panels operated at approximately 60°C, which was 15°C higher than expected. Consequently, the power capability calculated at this higher temperature revealed a potential shortage of power. This power deficiency was corrected by increasing the area of the solar array to permit the addition of 918 solar cells, increasing the total number of cells from 9792 to 10710. The increase in the number of solar cells enlarged the solar panel capability by 15 w at the maximum power point and 12 w at the battery sharing point.

Curves of anticipated panel temperatures, maximum power and maximum-power point voltage vs. Sun–probe distance in millions of km are shown in Fig. 4 and 5, respectively.

### D. Battery

In the design of the battery, the basic requirements were that this component must:

1. Provide power during launch

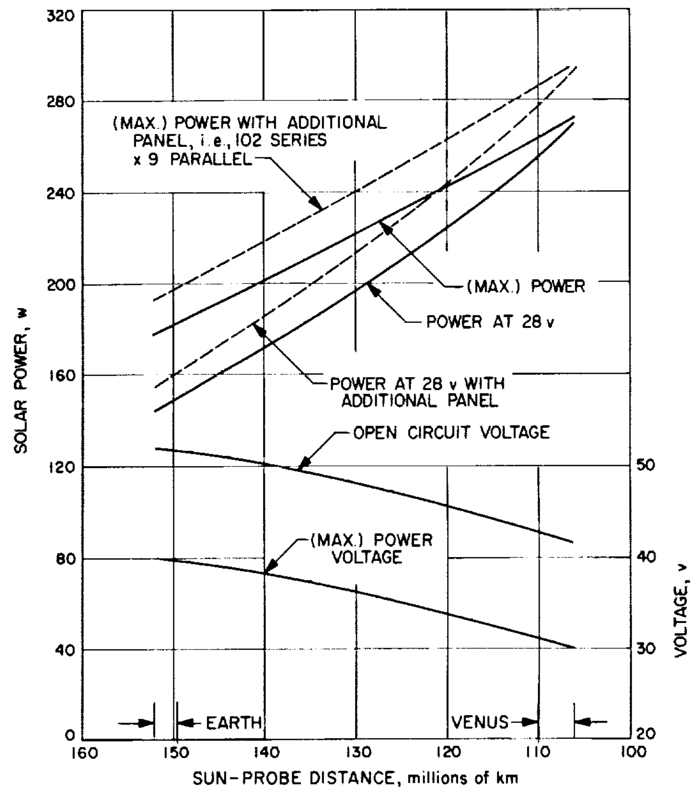


**Fig. 4. *Mariner* solar-panel power and voltage**

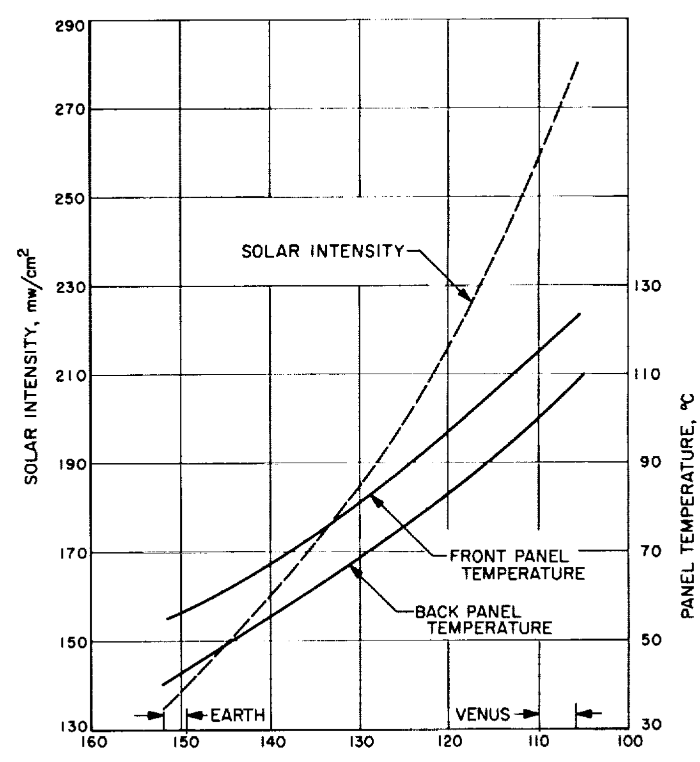


**Fig. 5. *Mariner* solar-panel temperatures**

2. Recharge during first cruise mode
3. Support midcourse maneuver power requirements
4. Support two possible reacquisition modes before encounter
5. Support a continuous load of less than 0.5 w during the cruise mode after midcourse, and
6. Fully recharge before encounter

The *Mariner* Venus spacecraft battery was constructed using sealed silver-zinc cells. It had approximately 40 amp-hr capacity and was recharged during the flight. Each unit was composed of an aluminum housing, two cell blocks (a total of 9 cells per block), two multiple-pin connectors, and two large terminal posts. The total battery with the 18 cells weighed 33.3 lb and the energy-to-weight ratio was approximately 40 w-hr/lb.

The battery characteristics were as follows:

| | |
|---|---|
| System | Rechargeable, sealed, silver zinc |
| Voltage range | 25.8 to 33.4 v |
| Current | 15 amp at 32 v for 10 ms |
| Cycles | 5 |
| Temperature range | 50 to 120°F |

### E. Design Problems and Restraints

In the usual spacecraft program, users of power begin the development of their equipment at the same time the power subsystem is developed. Thus, it is apparent that the power system cannot be developed properly until the load profile and voltage requirements are firmly known. This is true if the power source produces the variety of voltages required by the user. By applying a fixed ac voltage to the user, the principal variable in power-supply design is load uncertainty, and the voltage problem is transferred across the interface to the user, who must develop his own transformer rectifier system.

Some problems are created with this particular power distribution method. One of the problems noted was in the incompatibility between the peak power capability of the 2.4 kc amplifier and the high instantaneous-current demand of the capacitor input filters in several of the user T-R units. This problem was solved by incorporating choke input filters in those T-R units which were the major users of power.

A second problem was the lower-than-expected efficiencies exhibited by the user T-R units and regulators. In establishing the design criteria for the *Mariner* power system, a somewhat different and more logical approach was used for allocating the power output to the users. The input power to the T-R units, rather than the output power, was used as the controlled quantity, which resulted in more careful evaluation of the T-R unit characteristics by the user, particularly efficiency.

The requirements for the power-system design were to provide the power for the spacecraft loads and to comply with the desired attributes in the order of the priority given below:

1. Reliability
2. Efficiency
3. Weight
4. Conducted and radiated interference in relation to the interference susceptibility of the most critical subsystem in the spacecraft
5. Balancing of heat dissipation
6. Size

A restraint in maximum charging current was necessary to assure sufficient solar power for charging and providing the spacecraft loads at all times.

## II. OPERATIONAL CHARACTERISTICS OF THE POWER SYSTEM

The operation of the power system was sensitive to the orientation of the spacecraft and to the electrical loads. During the launch phase, the battery supplied the power, since the spacecraft solar panels were not oriented toward the Sun. When the spacecraft became Sun-oriented, the solar panels assumed the load and recharged the battery. For the remainder of the mission, the modes of operation are obvious; that is, when the spacecraft was Sun-oriented, the panels were the prime source of electrical energy; at other times, when the panels were not directed toward the Sun, the battery was the primary power source.

When the load exceeded the maximum power capability of the solar panels, or when the output from the solar panels was decreased because of spacecraft orientation, the solar panels and the battery shared the load. In either case, sustained operation was expected to deplete the store of energy in the battery and to result eventually in spacecraft failure. It had been anticipated that normally the sharing mode would be ended either by Sun reacquisition or reduction of load.

The mechanism of the sharing mode was of considerable interest. For most load conditions, there were two operating points for the solar-panel system: (1) high voltage and low current, and (2) low voltage and high current. Solar-panel characteristics were conveniently described in terms of power vs. voltage, as shown in Fig. 6. Analysis of the power system revealed that, for stable operation, the slope of the power-voltage characteristic must be negative. Clearly, then, the region to the right of the maximum-power point on the solar panel characteristic was stable, whereas the region to the left was unstable. In the *Mariner* system, operation to the left of the maximum-power point of the solar panel characteristic was stabilized by setting the maximum-power point above the battery voltage.

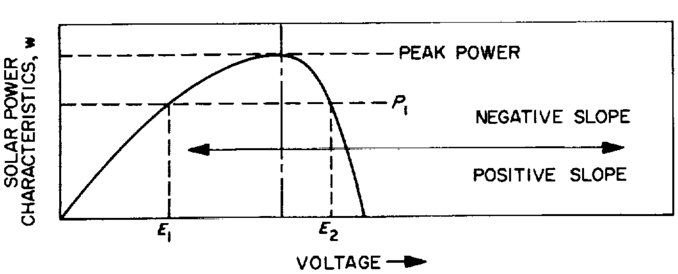


**Fig. 6. Solar-panel power**

The effect of combining battery and solar panel characteristics is illustrated in Fig. 7, in which the composite power is plotted as a function of voltage. The circuit logic which resulted in this characteristic is shown in Fig. 8.

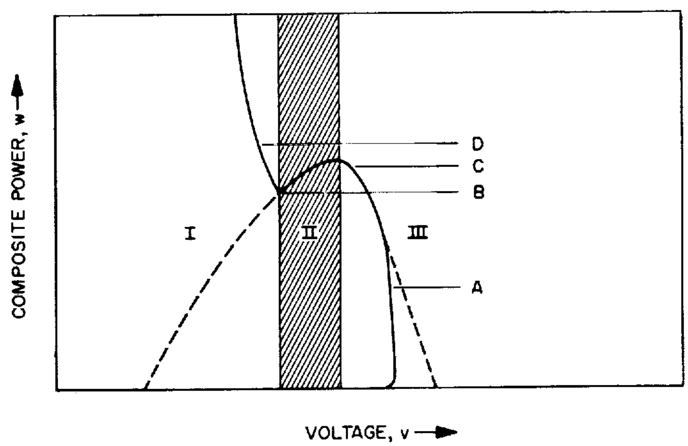


**Fig. 7. Composite power**

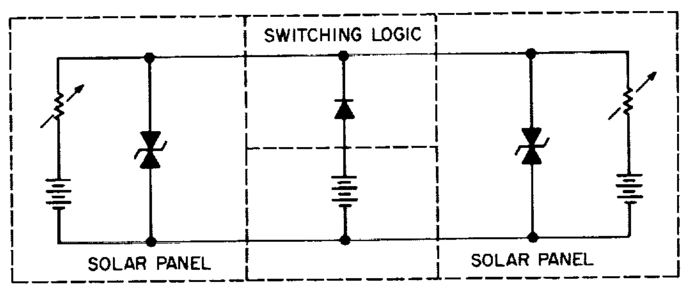


**Fig. 8. Electrical connections of power sources**

Note that the solar-panel characteristics were modified by the shunt zener diode, which reduced the voltage swing anticipated, but did not affect the stability of the system. The composite characteristic is shown as a solid line in Fig. 7, the solar-panel characteristic appears as a dotted line, and stable regions of operation are labeled I and III. Region II is unstable. The actual shape and size of the solar-panel portion of the characteristic curve were determined by the temperature of the panel, the incident solar intensity, and the degradation sustained because of radiation damage; hence, there was considerable uncertainty in the location of critical points on the curve.

For a given set of conditions (i.e., a fixed-composite characteristic), it is enlightening to examine the operation. If the power required was represented by the level A in Fig. 7, the operating point was at the intersection of A and the characteristic curve and was seen to lie in a stable region (III). If the load were increased from A to C, the operating point would still have remained in region III. However, were the load increased to level D, the operating point was expected to jump into region I. Between levels B and C, the voltage was multivalued; however, the operating point was expected to be in stable regions only. If the load was reduced from a value such as D, the curve was followed down to point B, whence the voltage jumped upon further reduction of load to a stable point in region III. Note that, in region I, the battery and the solar panel were expected to share the load; in region III, the solar panel carried the load alone.

In the sharing condition, the input voltage to the battery charger was the battery voltage; thus, no charging could occur. Generally speaking, sharing was an undesirable condition which, if continued, was expected to lead to the depletion of the battery and failure of the power system. The only way to escape the sharing mode was to reduce the load (power demand) below point B in Fig. 7.

In *Mariner*, the solar panel source was designed to provide sufficient power in the battery-sharing voltage so that the system would drop out of sharing when the spacecraft load was reduced from the peak demand to cruise mode operation. In addition, a capability of switching off a load (science) was incorporated to assure the drop-out from sharing if the panel characteristics deteriorated beyond the predicted values.

## III. POWER-SYSTEM PERFORMANCE BEFORE LAUNCH

All hardware of the power system was flight-acceptance tested prior to delivery to the spacecraft assembly area. One set of the hardware was type-approval tested. The type-approval tests subjected the equipment to extensive environmental testing to prove the electrical and mechanical design of the system.

The power system was installed in the spacecraft and was subjected to system tests at the spacecraft assembly facility. System, flight-acceptance, and type-approval testing presented some problems requiring rework of flight hardware.

During evaluation tests of the *Mariner* spacecraft, the 400-cps, 3-phase supply appeared to develop abnormal voltages when the unit was switched from single-phase to 3-phase operation. The problem was traced to high current arcing through a relay contact, and was corrected by replacing the relay with a new one which had the required current capacity.

A second problem occurred in the booster regulator of *Mariner 2* when the module showed abnormal operation during a high-load condition. The problem was traced to the unmatching characteristics between portions of the booster-regulator circuitry which, for packaging convenience, were housed in two modules. The problem was corrected by requiring that the flight-acceptance-tested modules be kept in pairs for proper operation.

Data on the leakage current of the solar-panel cells revealed that the series-connected blocking diodes in the power switch and logic modules could be removed. The elimination of these diodes reduced the power requirement by approximately 5 w. This added to the safety margin of solar-panel power operation during cruise condition.

All of the above modifications to the power system were effected before final system tests were performed.

## IV. POWER-SYSTEM PERFORMANCE FROM LAUNCH TO ENCOUNTER

*Mariner 2* spacecraft was successfully launched at approximately 0653 GMT on August 27, 1962. The power-supply system performed normally during all the phases of the spacecraft flight, launch, cruise, midcourse maneuver and encounter of Venus. Some problems were encountered during the flight; however, they did not hinder the operation of the power-supply system, because of redundancy. These problems are mentioned below:

1. October 31, 1962 (day 304): a short developed in one of the solar panels causing the spacecraft voltage to drop approximately 8.4 v. Because of the short, the power output of that panel dropped to zero and the other panel was supporting the spacecraft loads. The direct parallel connection of the panels (no diode isolation) caused a damping condition to the solar source voltage near the maximum power point of the power producing panel. This can be seen in the combined characteristics of the power producing and shorted panels shown in Fig. 9.

2. November 8, 1962 (day 312): the short on the panel recovered and all voltage returned to normal.

3. November 14, 1962 (day 318): the short on the same panel reappeared, and remained until the end of mission.

4. The battery temperature exceeded the upper design-temperature limit of 120°F. However, no failure was seen during encounter.

5. On December 30, 1962 (day 364): the 2.4 kc power supply frequency shifted to 2.2 kc. This frequency was the free-running frequency of the power system which indicated the loss of the synchronizing signal.

Curves of the power-system telemetry information (solar-panel output voltage and current, battery voltage, current and charge, and system temperature measurements) are shown in Figs. 10 through 19. Figure 10 shows the average readings of both panel voltages during the flight. The estimated values are also shown. The abrupt voltage drops were caused by the short developed in one of the panels. Figure 11 shows the output current of each panel. When the short developed in one of the panels, the power output produced by that panel dropped to zero, causing it to stop providing solar power to the spacecraft, and the spacecraft began receiving current

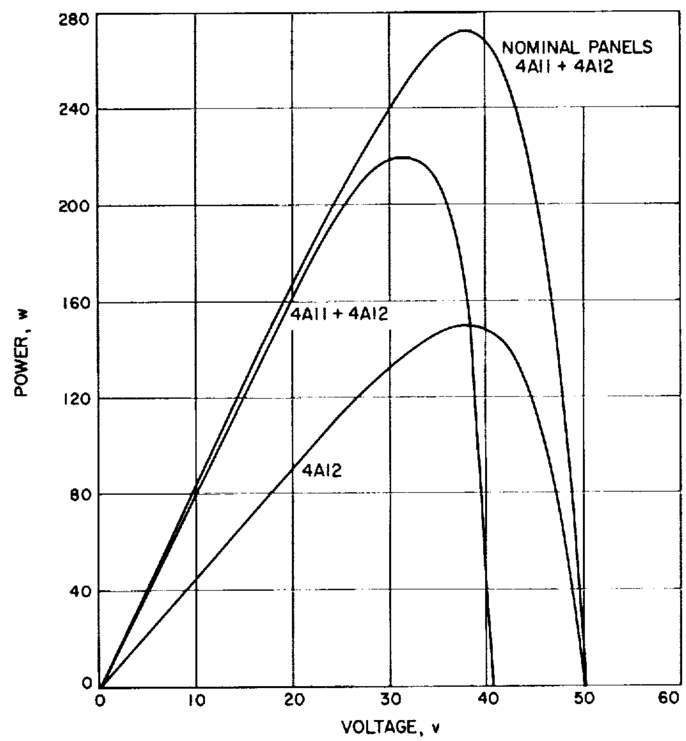


**Fig. 9. Combined panel characteristics**

from the other panel, as shown by the values marked. The power-producing panel was clamped at about its maximum power point. Figure 12 shows the battery voltage during the flight. The voltage dropped after 80 days of flight when the battery charger became inoperative because of the drop in solar source voltage. Figure 13 shows the battery drain and charge current. All activity in the battery current data stopped after the battery was charged. Figures 14, 15, and 16 show the temperature of the panels. The front temperature of both panels and the back temperature of one panel were measured. Figures 17, 18, and 19 show the temperature of the battery, booster regulator, and power-conversion equipment.

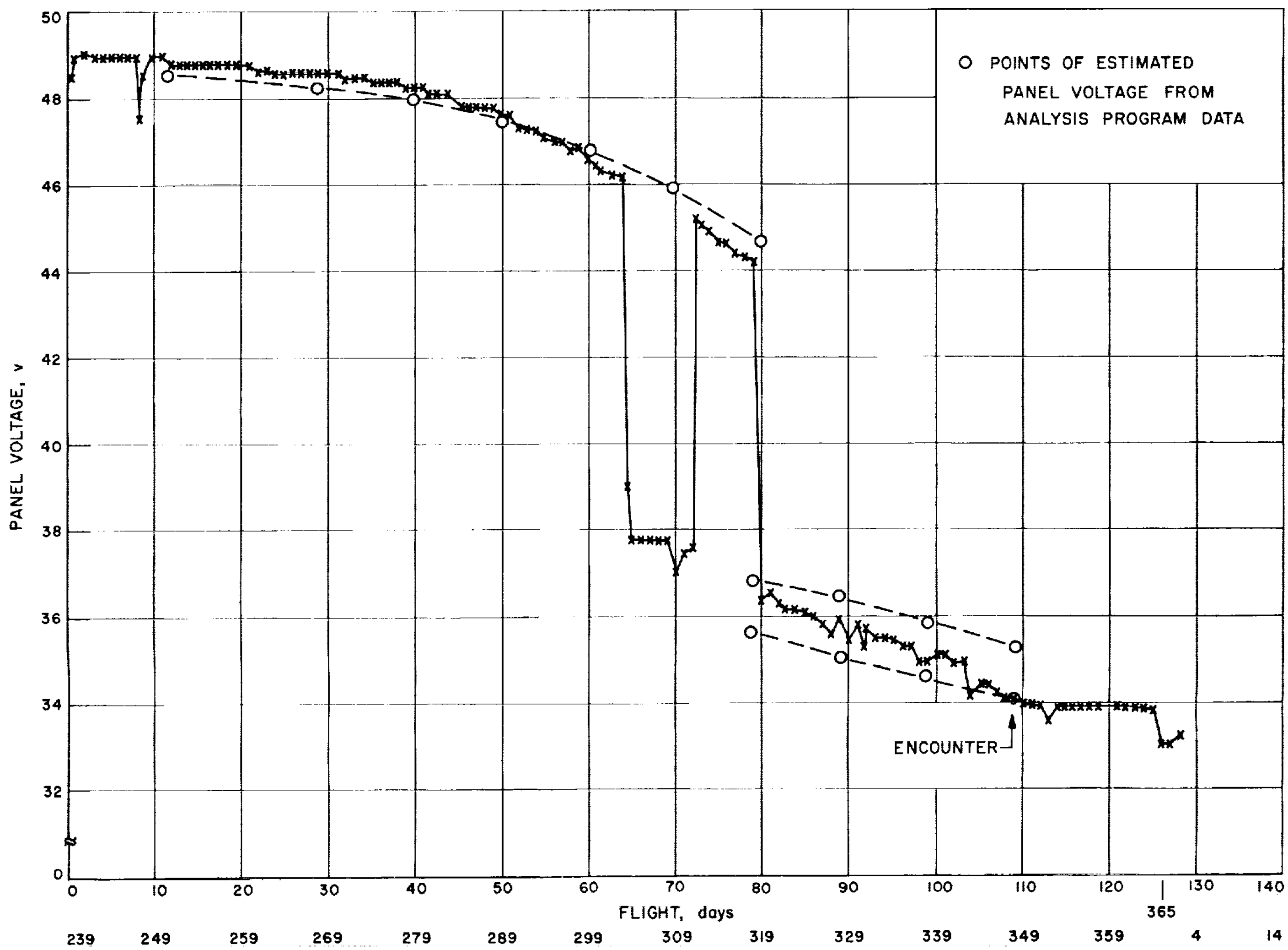


Fig. 10. Panel voltage, average reading of 4A11 and 4A12 *(Mariner 2)*

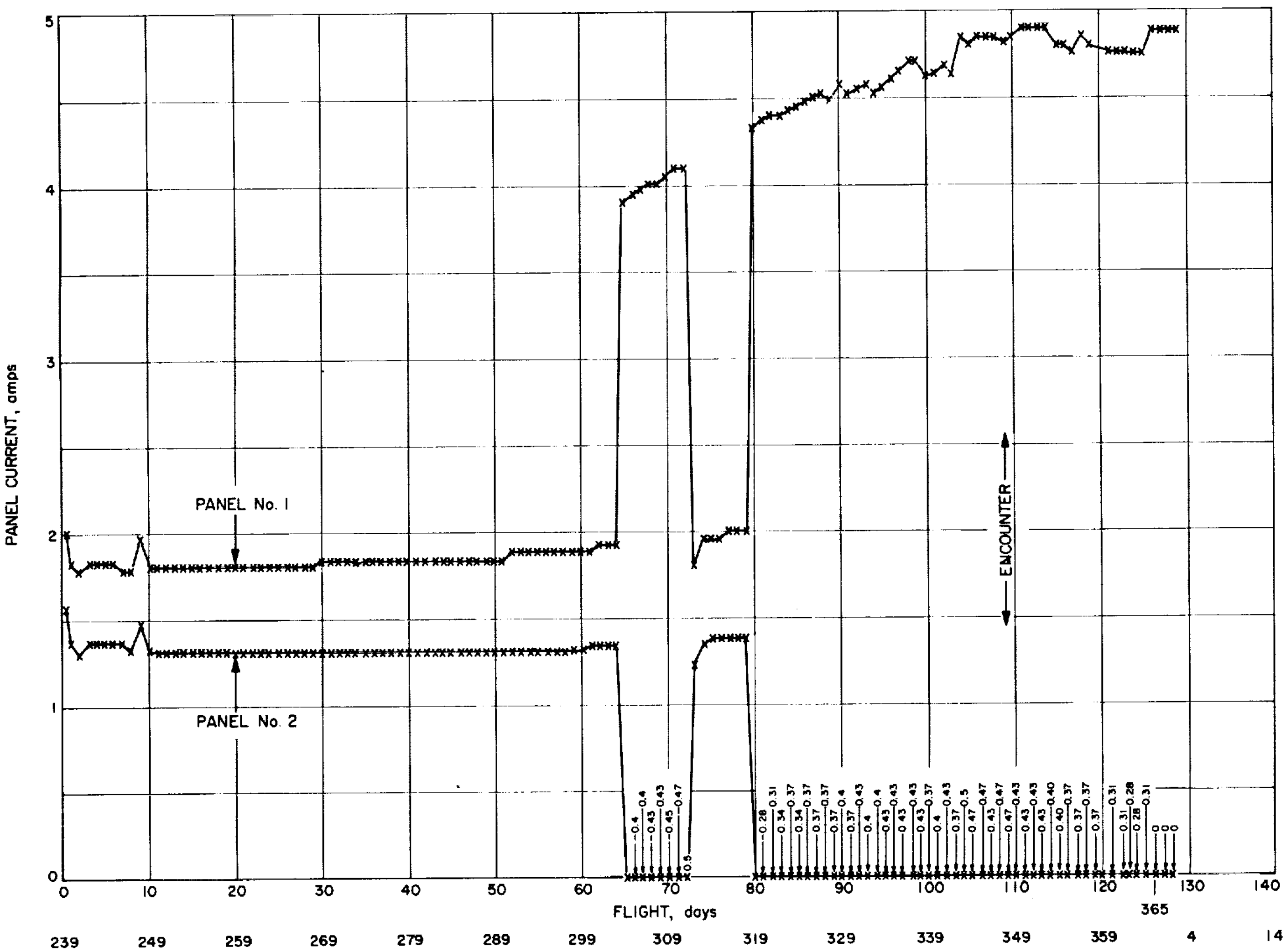


Fig. 11. Panel current 4A11 and 4A12 D5 D8 *(Mariner 2)*

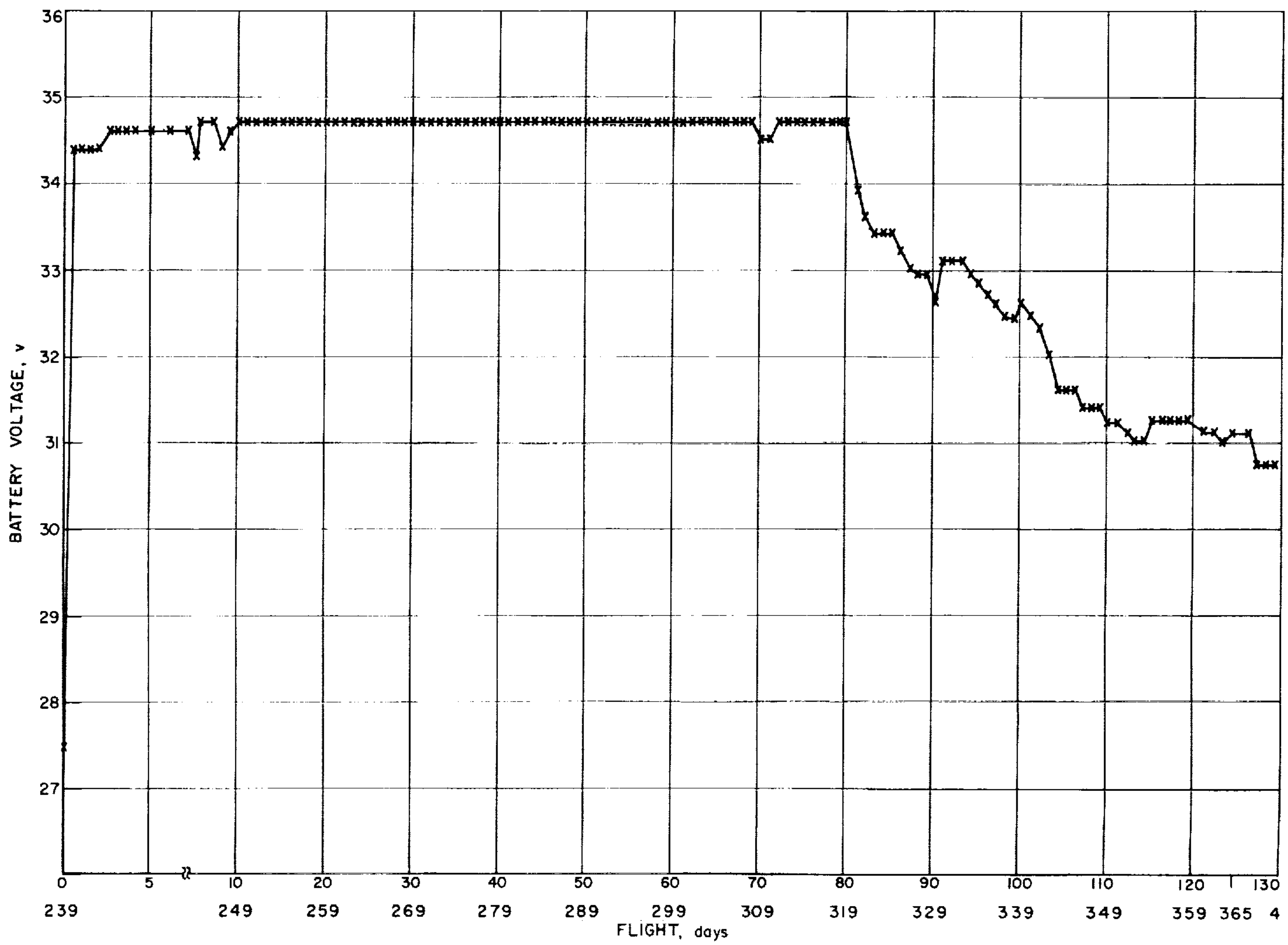


Fig. 12. Battery voltage A2 *(Mariner 2)*

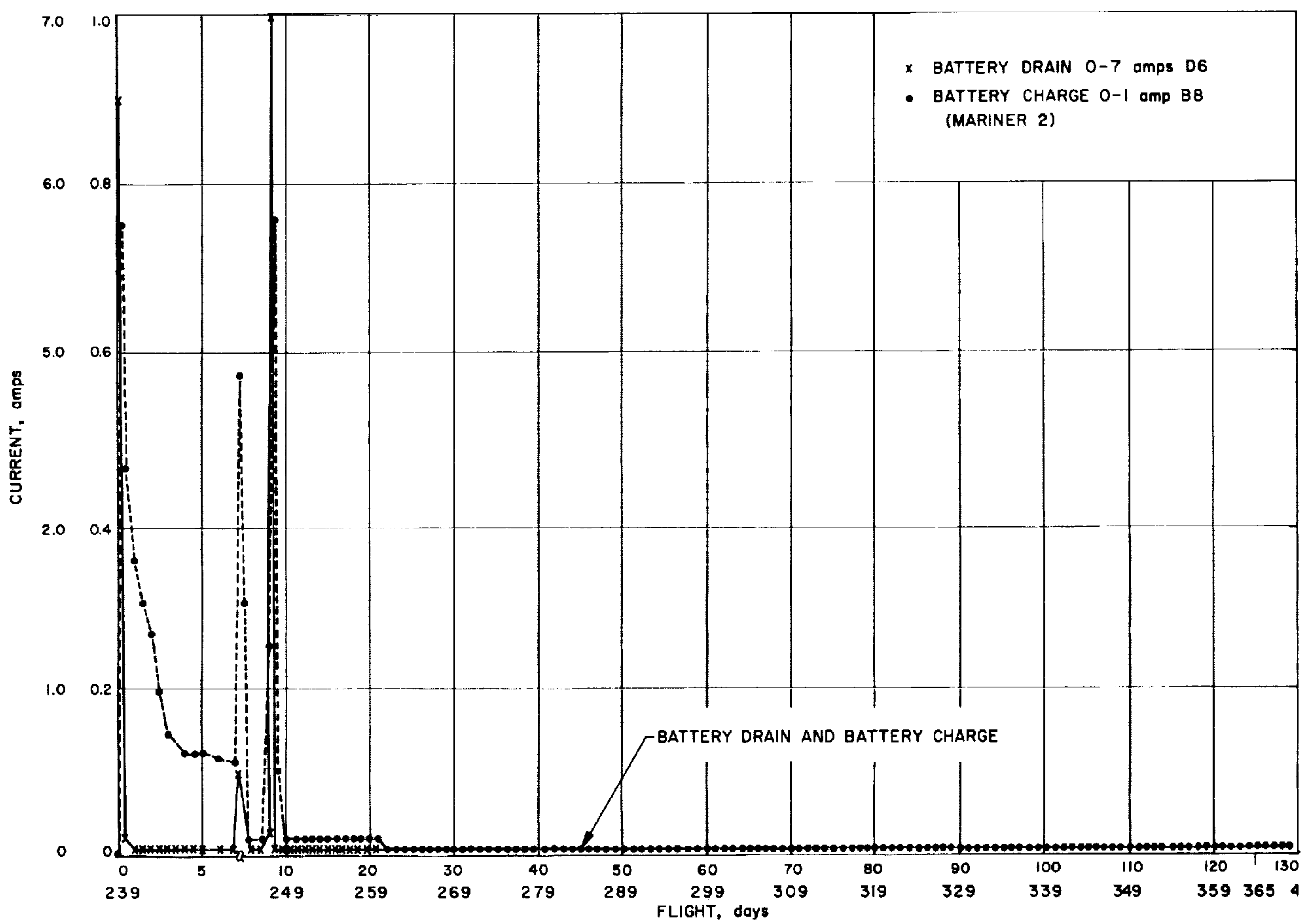


Fig. 13. Battery charge and drain characteristics

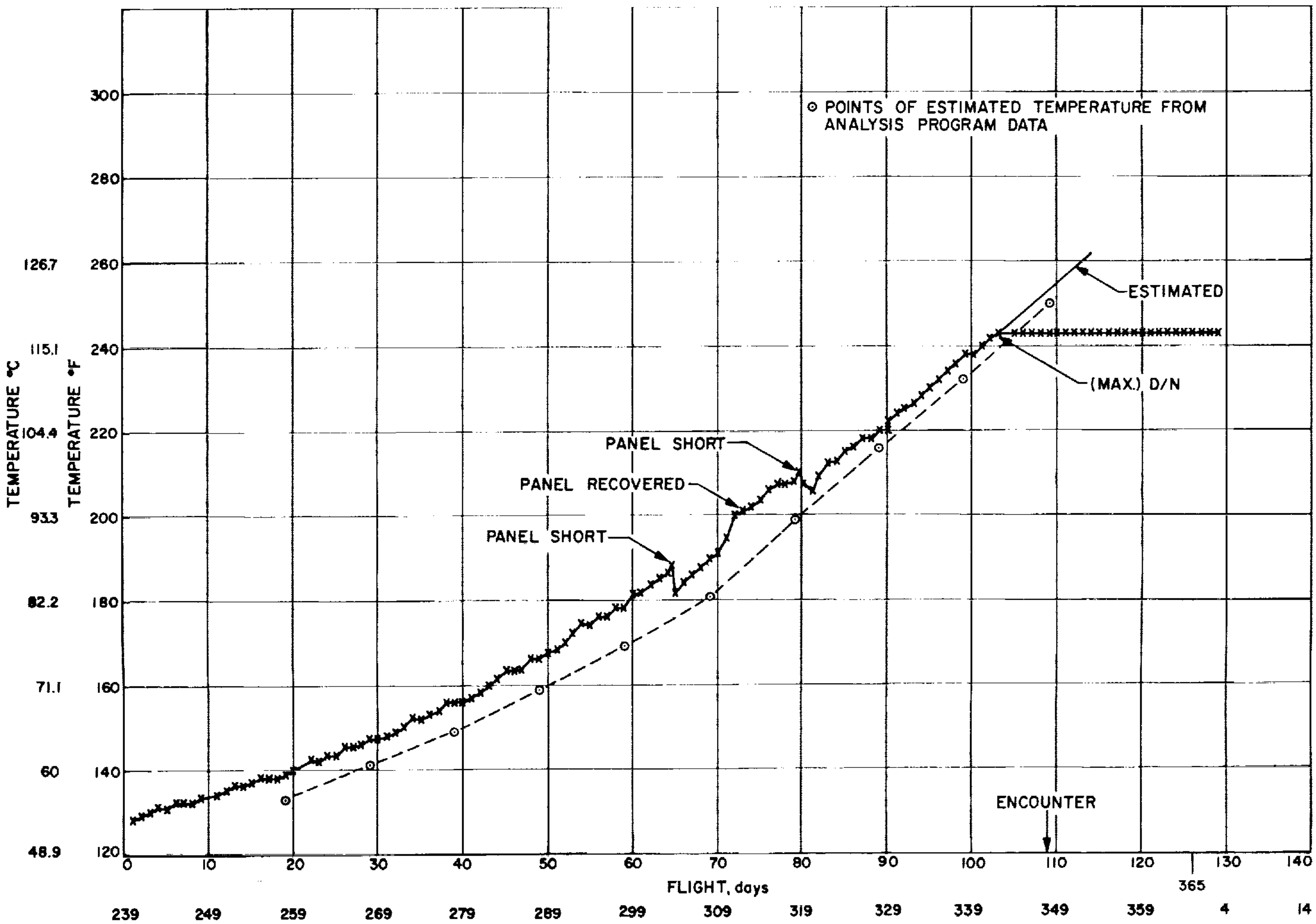


Fig. 14. Temperature of panel 4A12 front E8 *(Mariner 2)*

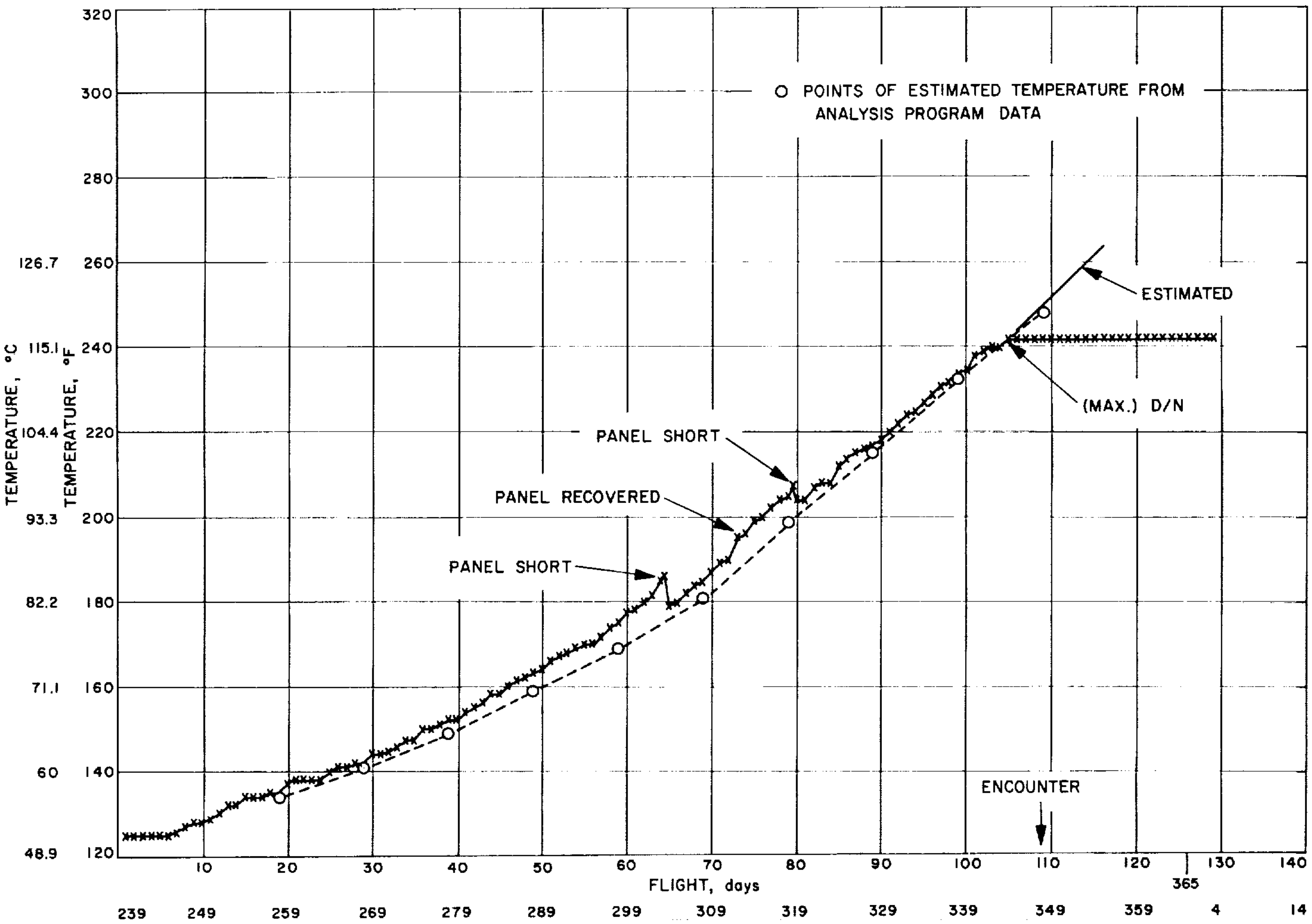


Fig. 15. Temperature of panel 4A11 front E7 *(Mariner 2)*

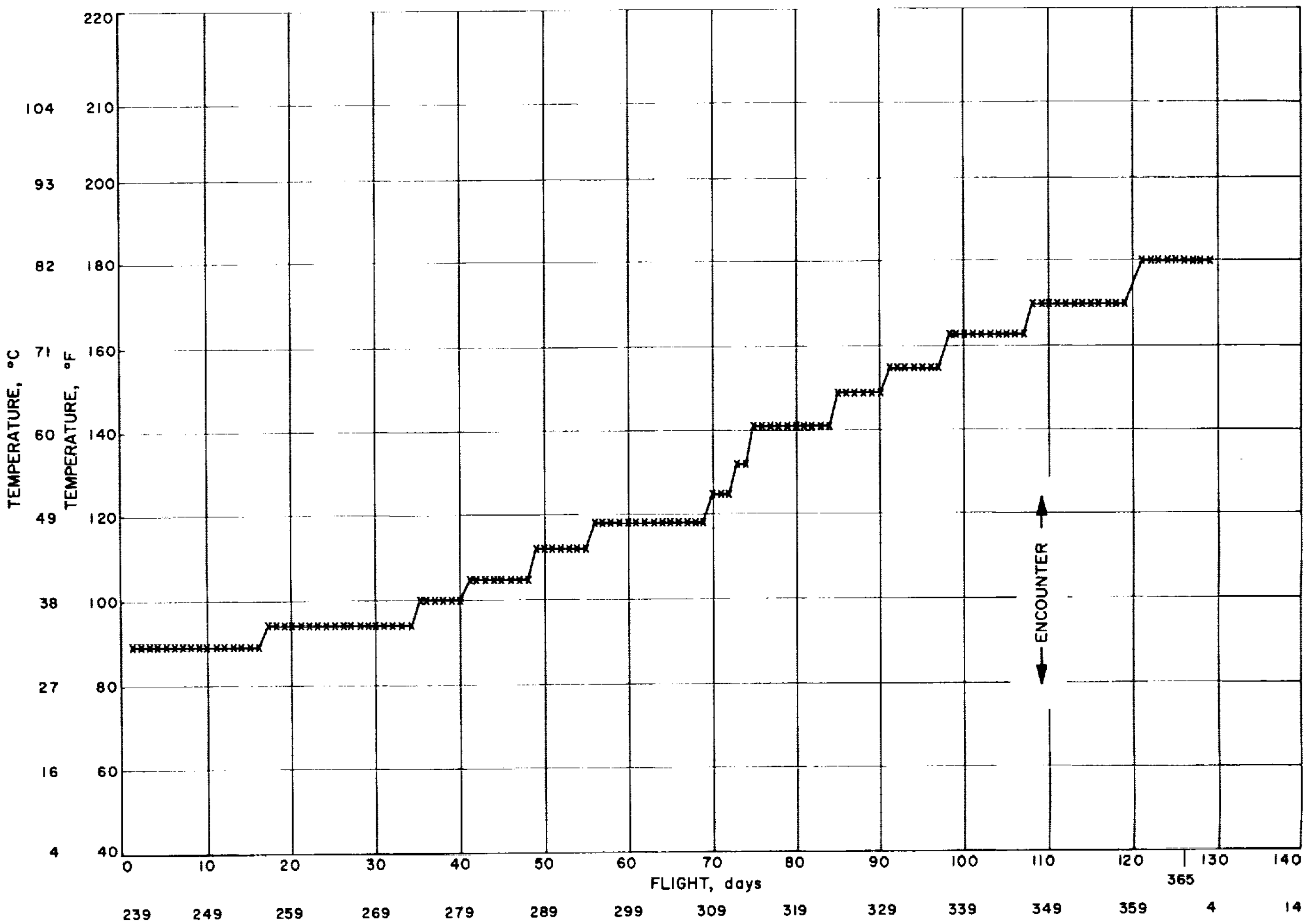


Fig. 16. Temperature of panel 4A11 back E9 *(Mariner 2)*

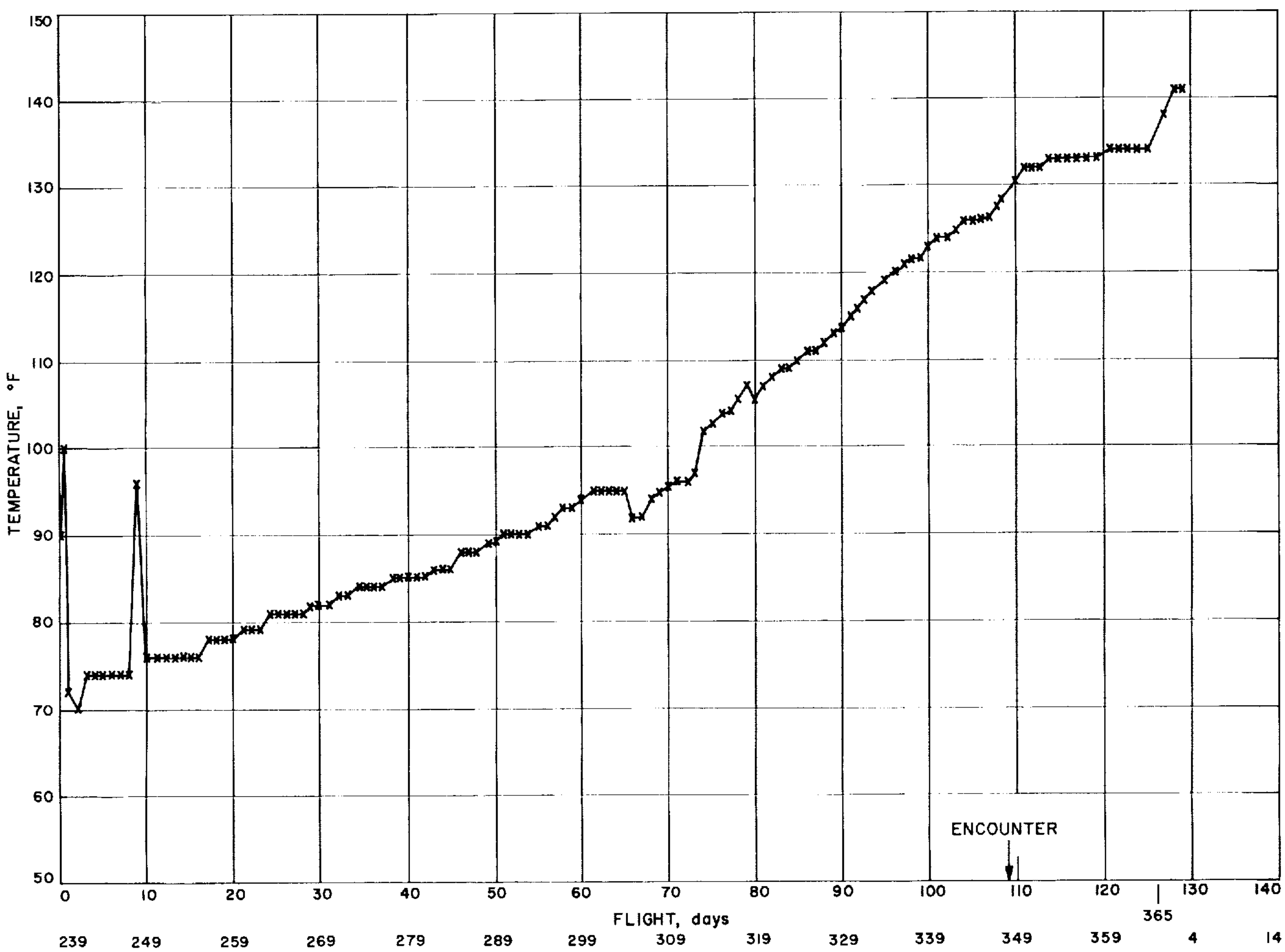


Fig. 17 Temperature of battery 4A14 E5 (*Mariner 2*)

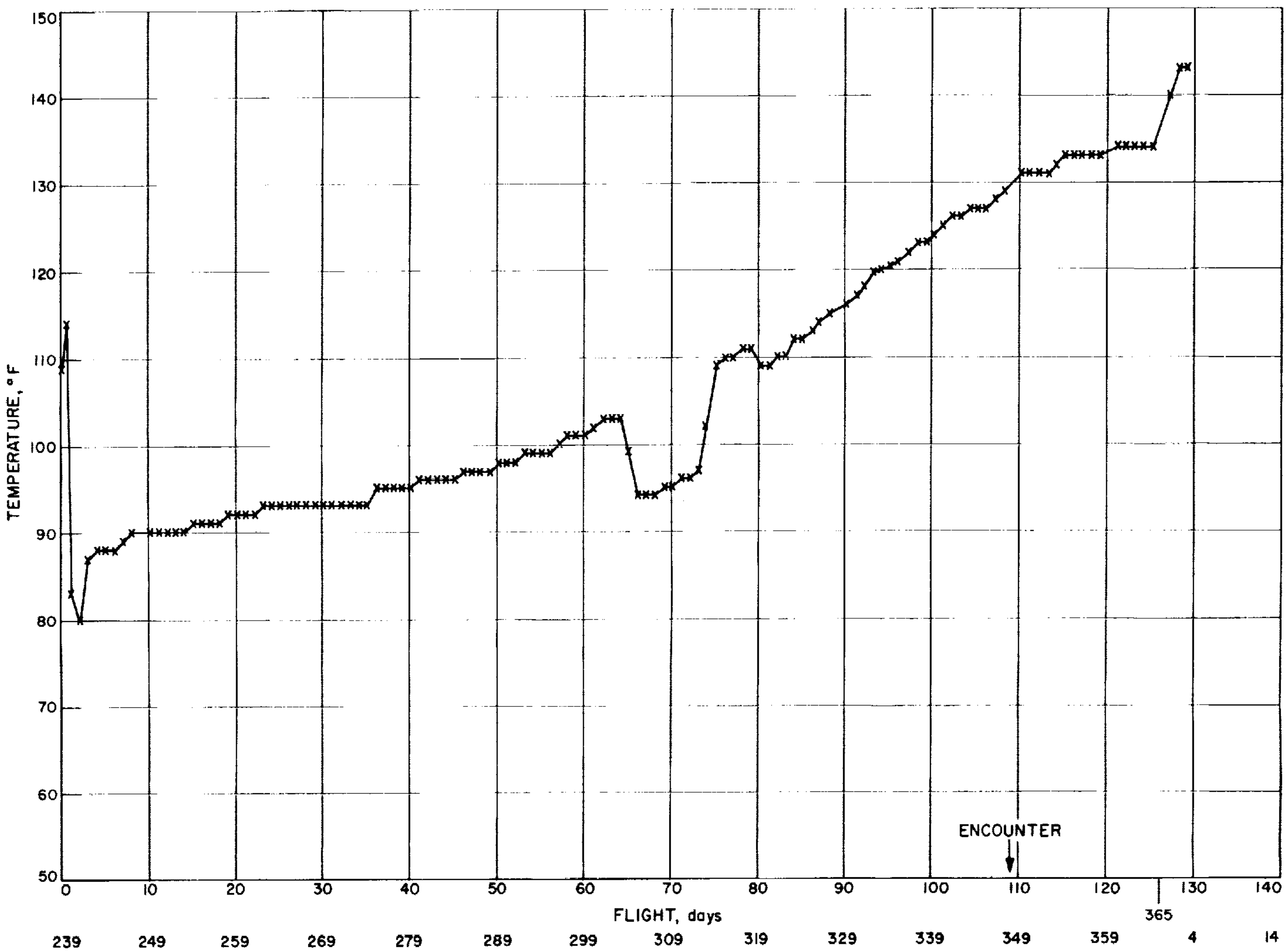


Fig. 18. Temperature of booster regulator E1 (*Mariner 2*)

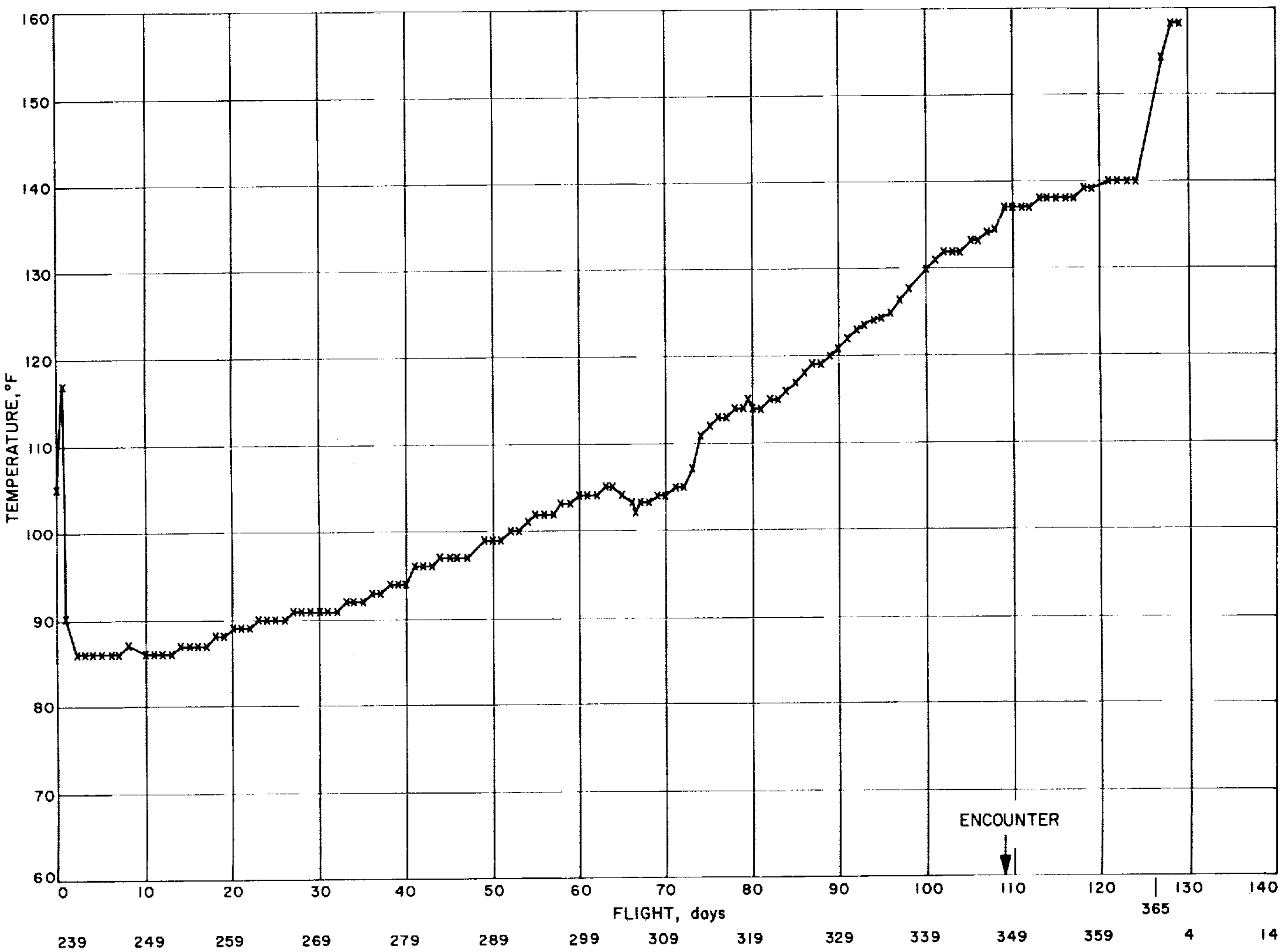


Fig. 19. Temperature of case V F4 (*Mariner 2*)

# V. CONCLUSION

The power system provided all energy required to operate the spacecraft and experiments. This has not been, however, without some abnormal behavior. Factoring out the abnormal experience, the performance has corresponded to that predicted. Solar power output before the short developed was as predicted without any degradation. Because of the high solar power available, no sharing during the expected periods occurred. Battery drain and charge were normal. Trickle charge of less than 5 ma remained continuously on the battery for more than 2 mo without destruction. Correspondence of the predicted and telemetered values appeared to be within and, considering telemetry accuracy of 3%, the design seems to be well confirmed.